

Expansion Velocities and Core Masses of Bright Planetary Nebulae in the Virgo Cluster

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ABSTRACT

The line-of-sight velocities and [OIII] 5007 Å expansion velocities are measured for 11 planetary nebulae (PNs) in the Virgo cluster core, at 15 Mpc distance, with the FLAMES spectrograph on the ESO VLT. These PNs are located about halfway between the two giant ellipticals M87 and M86. From the [OIII] 5007 Å line profile widths, the average half-width at half maximum expansion velocity for this sample of 11 PNs is $\bar{v}_{HWHM} = 16.5 \text{ kms}^{-1}$ (RMS = 2.6 kms^{-1}). We use the PN subsample bound to M87 to remove the distance uncertainties, and the resulting [OIII] 5007 Å luminosities to derive the central star masses. We find these masses to be at least $0.6 M_{\odot}$ and obtain PN observable life times $t_{PN} < 2000 \text{ yrs}$, which imply that the bright PNs detected in the Virgo cluster core are compact, high density nebulae. We finally discuss several scenarios for explaining the high central star masses in these bright M87 halo PNs.

Subject headings: Planetary nebulae: general. Galaxies: M87, distance and redshift, halos. Galaxies: clusters: Virgo cluster

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1. Introduction

Since the discovery of free-floating intracluster planetary nebulae (ICPNs) in the Virgo cluster (Arnaboldi et al. 1996), extensive imaging and spectroscopic observations were carried out to determine their projected phase space distribution and the fraction of diffuse cluster light not bound to Virgo galaxies. To enlarge the sample of more than 40 ICPN line-of-sight (LOS) velocities available from Arnaboldi et al. (2003, 2004), we have obtained new PN spectra with FLAMES at the ESO VLT (Doherty et al. 2008). The high spectral resolution of the new data allows us for the first time to measure expansion velocities for the [OIII] nebula shells of 11 PNs in the Virgo cluster core, nearly half way between M87 and M86. The expansion velocity of a planetary nebula (PN) is one of the most important parameters determining its evolution, but currently it is known only for a few hundred Galactic PNs, mostly bright objects in the Milky Way Disk (Gesicki & Zijlstra 2000), and for a few tens in the Magellanic Clouds and M31. When interpreted using dynamically evolving nebular models (e.g. Schönberner et al. 2005), PN shell expansion velocities provide reliable estimates of PN dynamical ages and distance estimates for Galactic PNs.

In this letter, we give a brief summary of our Observations in Section 2. In Section 3, we present the PN [OIII] 5007 Å half-width half maximum velocity measurements v_{HWHM} , and $m(5007)$ magnitudes as defined by Jacoby (1989). In Section 4 we build the PN luminosity function (PNLF) for the spectroscopically confirmed PN sample in Virgo and for the subsample bound to the M87 halo. In Section 5, we then estimate the outer radii of the M87 halo PNs from the observed PN expansion velocities and their visibility lifetimes. We finally discuss in Section 6 the remaining distance uncertainties, the shape of the PNLF in the M87 halo, and the mechanisms that may be responsible for the large core masses of the brightest PNs in the halo of M87.

2. Observations

Data were acquired in service mode (22 hrs, 076.B-0086 PI: M. Arnaboldi), with the FLAMES spectrograph at UT2 on VLT in the GIRAFFE+MEDUSA configuration. We used the high-resolution grism HR 504.8, covering a wavelength range of 250 Å centered on 5036 Å and a spectral resolution of ~ 20000 . The redshifted [OIII] emissions of PNs in the Virgo cluster core fall near the center of the grism transmission. With this setup, the instrumental broadening of the arc lines is $\text{FWHM} = 0.29 \text{ Å}$ or 17 kms^{-1} , and the error on the wavelength measurements is 0.0025 Å or 150 ms^{-1} (Royer et al. 2002). A total of three FLAMES plate configurations were produced for the Virgo core fields F4 and F7 surveyed by Feldmeier et al. (2003). The exposure times were based on the signal-to-noise

ratio (S/N) estimate for detecting the [OIII] 5007 Å line flux of $4.2 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$, i.e., $m(5007) = 27.2$, with $S/N \sim 5$. The data reduction was carried out with the GIRAFFE pipeline, for the CCD prereduction, fiber identification, wavelength calibration, geometric distortion corrections, co-addition, and extraction of the final one-dimensional spectra. Data analysis and the velocity measurements are presented in Doherty et al. (2008). A total of 12 PNs were confirmed spectroscopically. In the extracted PN spectra, the [OIII] 5007 Å emissions of 11 PNs have measured FWHM between 0.4 and 0.7 Å; the comparison with the arclines’ FWHM (0.29 Å) indicates that these [OIII] emission lines are resolved. Monte Carlo simulations give an error on the line width measurements of 0.0025 Å for a S/N per pixel of ~ 15 (Royer et al. 2002).

3. PN expansion velocities

The spectroscopic expansion velocity measured from the [OIII] 5007 Å line profile appears to be representative for the material velocities associated with the PN bright rim¹, and is systematically lower than the expansion speed of the PN shell’s outer radius, according to 1D hydrodynamical simulations (Schönberner et al. 2005). The shell expansion velocities are associated with fainter structures at larger radii, which have been measured only for Galactic PNs (Corradi et al. 2007).

From the FLAMES PN spectra, we are able to measure the spectroscopic expansion velocities from the resolved [OIII] 5007 Å emissions for 11 PNs in the Doherty et al. (2008) sample; high S/N spectra for 4 PNs are shown in Fig. 1. We use the “half-width at half maximum” of the [OIII] 5007 Å line, corrected for the instrumental half width, v_{HWHM} , as measurement of the spectroscopic expansion velocity for the PN bright rim. According to Schönberner et al. (2005) and Corradi et al. (2007), these v_{HWHM} measurements must be multiplied by a factor of about two to get an estimate of the PN’s true expansion velocity. When it is possible, we also measure the spectroscopic expansion velocities for [OIII] 4959 Å. When double peaks or secondary peaks are present in the resolved line profiles, their counts are consistent with the noise. The average [OIII] spectroscopic expansion velocity for this PN sample is $\bar{v}_{HWHM} = 16.5 \text{ kms}^{-1}$, with an RMS dispersion of 2.6 kms^{-1} . Both values are significantly smaller than those determined for samples of PNs observed in the Galactic bulge (Gesicki & Zijlstra 2000). The Virgo PNs might represent the [OIII] brightest part of the Galactic bulge population, or they might come from an entirely different population; this issue requires further work.

¹The bright rim is the thin shell well behind the outer shock, enclosing the wind-blown cavity of a PN.

Based on LOS velocities, we divide the current dataset in two subsamples: 5 PNs are associated with the halo of M87, i.e. belong to a narrow velocity peak in the LOS velocity distribution (LOSVD) centered at the M87 systemic velocity, with $RMS = 78 \text{ kms}^{-1}$ (Doherty et al. 2008), and 6 are “free-flying” cluster PNs, with $300 - 1500 \text{ kms}^{-1}$ velocity differences. The distributions of the v_{HWHM} measurements for the two subsamples are similar within the limited statistics, see Fig. 2; the KS-test gives only a 55% probability that the two subsamples are different. The v_{HWHM} vs. $m(5007)$ plot in the top panel of Fig. 2 shows that the PNs within 0.7 mags of the bright cut-off have $v_{HWHM} < 20 \text{ kms}^{-1}$. This is in agreement with the predictions of the spatially integrated line profile v_{HWHM} vs. $m(5007)$ computed with the nebular 1D hydrodynamics code of Schönberner et al. (2007, and in prep.) for central star masses in the range $0.696 - 0.625 M_{\odot}$.

When a PN’s distance is known, its expansion velocity and size can be used to determine its dynamical age. This age, in turn, can be combined with information about the central star’s effective temperature to yield an estimate of the core mass (Gesicki & Zijlstra 2007). In our case we cannot measure the outer radii for the Virgo PNs, as they are unresolved at a distance of 15 Mpc. Our approach is then the reverse: we shall estimate the central star masses from the [OIII] 5007 Å fluxes, derive the PN lifetimes t_{PN} from central star evolutionary tracks and nebular 1-D hydrodynamical models, and infer their physical dimensions as $r_{PN} = v_{exp} \times t_{PN}$, where $v_{exp} = 2 \times v_{HWHM}$ (Schoenberner et al., in prep.).

4. The M87 halo PNLF

The PNLF for the spectroscopically confirmed PNs in the Virgo core region around M87 is shown in Figure 3. The brightest PNs have $m(5007)$ in the range $25.7 - 26.5$. PNs with similar magnitudes were also detected by Ciardullo et al. (1998) in the outer regions of M87. Based on a sample of 338 PNs, Ciardullo et al. (1998) determined a brightening of the PNLF cutoff of 0.37 mag for the PN subsample at $R > 4'$ with respect to the sample inside $R \leq 4'$. They interpreted the brightening of the PNLF in the M87 outer halo as due to a population of Virgo ICPNs filling the elongated volume of the Virgo cluster (up to 4 Mpc along the LOS). The number of foreground PNs would be roughly proportional to the area of the field, and therefore be largest in the outer regions of the surveyed field.

In our spectroscopic PN sample we can bypass the distance ambiguity by selecting the subsample of 14 PNs² bound to M87. These PNs are associated with a narrow peak in the LOSVD centred at the systemic velocity of M87, see Fig. 3. Their average velocity

²5 PNs from the Doherty et al. (2008) sample and 9 from the F3 field from Arnaboldi et al. (2004)

$v_{LOS} = 1306 \text{ kms}^{-1}$ and the $RMS = 117 \text{ kms}^{-1}$. The empirical PNLf for the M87 halo PNs is shown in Fig. 3: their $m(5007)$ magnitudes are in the range $26.2 - 27.2$, indicating a slightly brighter cut-off than for the PN population in the central $R \leq 4'$ region of M87. However we can now say that this is an intrinsic property of the PN halo population, as we now know that these 14 PNs are all at the distance of M87 within $\sim 100 \text{ kpc}$ (see also §6).

5. PN core masses, visibility time scales and outer radius

From the measured $m(5007)$ of the M87 halo PNs, we estimate the central star total luminosity. Both models and observations indicate that no more than 10% of the central star's total luminosity comes out in this line (Jacoby 1989). Therefore the intrinsic luminosity of the post-AGB star that powers an $m(5007) = 26.2$ PN at 14.5 Mpc must be $> 6930 L_{\odot}$ and, based on the evolutionary tracks of Blöcker (1995), we thus obtain a central core mass larger than $0.6 M_{\odot}$. Using a 1-D hydrodynamics code and the stellar evolution tracks of (Blöcker 1995), Schönberner et al. (2007) computed the nebular physical parameters and evolution of $m(5007)$ as function of nebular age, from near the AGB phase to the white dwarf cooling tracks. The nebular tracks of Schönberner et al. (2007, Fig. 15) that reach the brightest 0.5 mag of the PNLf, and have a central core mass of $> 0.60 M_{\odot}$ as the Virgo PNs, have very short visibility lifetimes, $t_{PN} < 2.0 \times 10^3 \text{ yrs}$. From our measurements and $v_{exp} = 2 \times v_{HWHM}$, we can then determine the outer radii r_{PN} of the brightest PNs in the M87 halo to be $\sim 0.07 \text{ pc}$. The nebular shells of these PNs are compact and similar to those observed for the brightest ($\log L \geq 3.8$) Galactic Bulge PNs.

6. Discussion

Distance uncertainties and PNLf brightening - We briefly consider the question whether the bright PNe in the velocity range bound to M87 could be foreground objects. The mean heliocentric velocity of the Virgo cluster is $< v_{\odot} >_{VC} = 1050 \pm 35 \text{ kms}^{-1}$ (Binggeli et al. 1993). M87 is redshifted by about 300 kms^{-1} ($v_{M87} = 1307 \text{ kms}^{-1}$) with respect to the Virgo cluster mean velocity, and is falling into Virgo from in front (Binggeli et al. 1993) towards M86 (Doherty et al. 2008).

PNs at the cutoff $m^* = 26.33$ with apparent magnitudes $26.2-26.0$ would be between $\sim 1 - 3 \text{ Mpc}$ in front of M87. Diffuse light stars at these locations would be in the infall region towards Virgo where the infall velocities are of order 1000 kms^{-1} and vary rapidly with distance (Mohayee & Tully 2005, and references therein). On the other hand, radial

velocities of $\sim 1300 \text{ km s}^{-1}$ would be expected for foreground objects $\sim 6 \text{ Mpc}$ in front of the Virgo core. It is thus very unlikely that a distribution of foreground PNe should be observed in our fields at exactly the systemic velocity of M87, with a dispersion of only $\sim 100 \text{ km s}^{-1}$, and less likely still that this population should be projected onto the M87 halo inside 150 kpc but not be observed in the adjacent Virgo core region covered by our data.

While the Virgo cluster has a significant depth ($\sim \pm 2 \text{ Mpc}$), it is unlikely that the diffuse light and ICPN distribution are similarly elongated. The search for ICPNs outside the Virgo cluster core has given negative results (Castro et al. 2008, in prep.), and the deep photometry of Mihos et al. (2005) shows that the diffuse light is mostly associated with the giant elliptical galaxies, M87, M86 and M84, whereas its surface brightness decreases sharply at larger radii. Observations of the diffuse light in $z = 0.25$ galaxy clusters also show that it is more centrally concentrated than the cluster galaxies (Zibetti et al. 2005), in agreement with cosmological simulation of cluster formation (Murante et al. 2007). Thus we can safely conclude that the selected M87 halo PNs are bound to M87, and that their bright [OIII] magnitudes are an intrinsic property of this PN population.

Mechanism leading to large core masses in the M87 halo PNs - The initial mass-final mass relation (IFMR) for solar metallicity stars predicts that the PN progenitors with $\sim 2.2 M_{\odot}$ give final core masses of $0.62 M_{\odot}$ (see Ciardullo et al. 2005; Buzzoni et al. 2006). Turnoff masses of $\sim 2 M_{\odot}$ belong to populations with ages $\sim 1 \text{ Gyr}$ (Iben & Laughlin 1989). The question is whether such populations exist in the M87 halo or in the Virgo diffuse stellar light. Observations in the V, I bands of the stellar population in a 11.39 arcmin^2 field halfway between M87 and M86 were carried out with the Advanced Camera for Survey (ACS) and the HST. This location falls within the F4 Virgo field of Feldmeier et al. (2003) and is included in the area surveyed by Doherty et al. (2008). At this location, Williams et al. (2007) detected some ~ 5300 intracluster red giant branch stars (IRGB); from the color magnitude diagram (CMD), they estimated the age and metallicity distribution of the parent stellar population. In this region, 70% - 80% of the Virgo IRGB are old ($> 10 \text{ Gyr}$), and span a wide range of metallicities ($-2.3 < [M/H] < 0.0$), with a mean value of $[M/H] \sim -1.0$.

From the number of PNs within 0.5 mag of the PNLF cut-off, $N_{0.5}$, we can determine how much luminosity would be present in an intermediate age population and compare it with the measured surface photometry of Mihos et al. (2005) in the surveyed region and the Williams et al. (2007) fit to the IRGB CMD. If we assume the analytical formula of Ciardullo et al. (1989) for the PNLF, then $N_{0.5} = N_{PN}/100$, where N_{PN} is the total number of PNs associated with the luminosity of the parent stellar population. The luminosity-specific PN number $\alpha = N_{PN}/L_{gal}$ is given by Buzzoni et al. (2006) for stellar populations with different ages and metallicities, and calibrated using the PN population in the Local

Group, Leo group, and the Virgo and Fornax clusters. The maximal theoretical value of α which gives the largest PN population for a given luminosity is $\alpha_{max} = 1PN \times (1.85 \times 10^6 L_{\odot})^{-1}$. This theoretical maximal value is independent of metallicity, and also provides an upper limit to the observed α for the PN population in different galaxy types (Buzzoni et al. 2006).

In the M87 halo, we have $N_{0.5} = 9 \pm 3$, which gives a total population of $N_{PN} = 900$ and a minimal bolometric luminosity of the parent population of $L_{gal} = N_{PN}/\alpha_{max} = 1.66 \times 10^9 L_{\odot}$ over a total surveyed area of 570 arcmin². We can thus derive a lower limit to the mean surface brightness in the V band, $\mu_V = 28.6$ mag arcsec⁻², for a possible intermediate age parent population. Comparing with $\mu_V = 28.3$ measured by Mihos et al. (2005) at the position of the Williams et al. (2007) field, we find that, to justify the number of bright PNs, at least 50% of the stars in this field would need to come from a 1 Gyr population. However, the upper limit to the contribution of a younger (< 10 Gyr) component to the IRGB stars given by Williams et al. (2007) is 30% - 20%. We must then conclude that there are not enough intermediate age stars in the Williams et al. (2007) field to justify the observed $N_{0.5}$.

What are the possible alternatives, if an intermediate age population is not present? The Williams et al. (2007) results indicate that the Virgo core population of stars is dominated by low metallicity stars ($[M/H] \leq -1$) with ages > 10 Gyr; thus we may argue that the halo of M87 may be also metal poor. In this case, the PNLf might have a bright cutoff that is different from that of a metal rich population. However Dopita et al. (1992), and PNLf observations in metal-poor galaxies (Ciardullo et al. 2002) show that metal poor systems have values of M^* that are fainter than those of their metal-rich counterparts. Also the Oxygen abundance measurements by Méndez et al. (2005) of the brightest extragalactic PNs in NGC 4697 indicate near solar metallicities for these stars. Therefore PN evolution from a metal poor population is unlikely to be a viable explanation for the observed large core masses in the M87 halo PN. The evolution of single stars from a 10 Gyr old population leads to central star masses in the range $0.52 < M < 0.55 M_{\odot}$ (Buzzoni et al. 2006), which cannot supply the $[OIII] \ 5007\text{\AA}$ flux required at the PNLf bright cut-off of $M^* = -4.48$. This led Ciardullo et al. (2005) to propose an alternative form of evolution, i.e close binaries and blue stragglers stars, as the likely progenitors of $[OIII]$ - bright PNs in a 10 Gyr old stellar population. This evolutionary channel seems better in agreement with the observations for the brightest PNs in the M87 halo, than either the ~ 1 Gyr-old or the metal-poor progenitors.

7. Conclusions

We have measured the nebular [OIII] 5007Å spectroscopic expansion velocities for 11 PNs in the Virgo cluster core, at 15 Mpc distance, with the FLAMES spectrograph on the ESO VLT. Based on the [OIII] line profile width, the average spectroscopic expansion velocity for this sample is $\bar{v}_{HWHM} = 16.5 \text{ kms}^{-1}$ (RMS = 2.6 kms^{-1}), which is in agreement with the predictions of dynamically evolving nebular models for high density nebulae close to their maximal $m(5007)$ emission. Large central star masses $M_{CS} > 0.6 M_{\odot}$ are inferred from the bright measured [OIII] luminosities and the known distance for the PNs bound to the M87 halo. From the large central star masses and the measured v_{HWHM} , we derive short PN visibility times and small nebular outer radii, $\sim 0.07 \text{ pc}$. The PNs in the M87 halo have large central star masses, are compact and their nebula shells may be similar to those observed for the brightest Galactic Bulge PNs. Three mechanisms are reviewed as possible explanation for the large core masses of the M87 halo PNs: intermediate age population, metallicity effects, and blue stragglers, with the latter being the most likely, given the old age and the low metallicities of the IRGB stars in the Virgo core (Williams et al. 2007).

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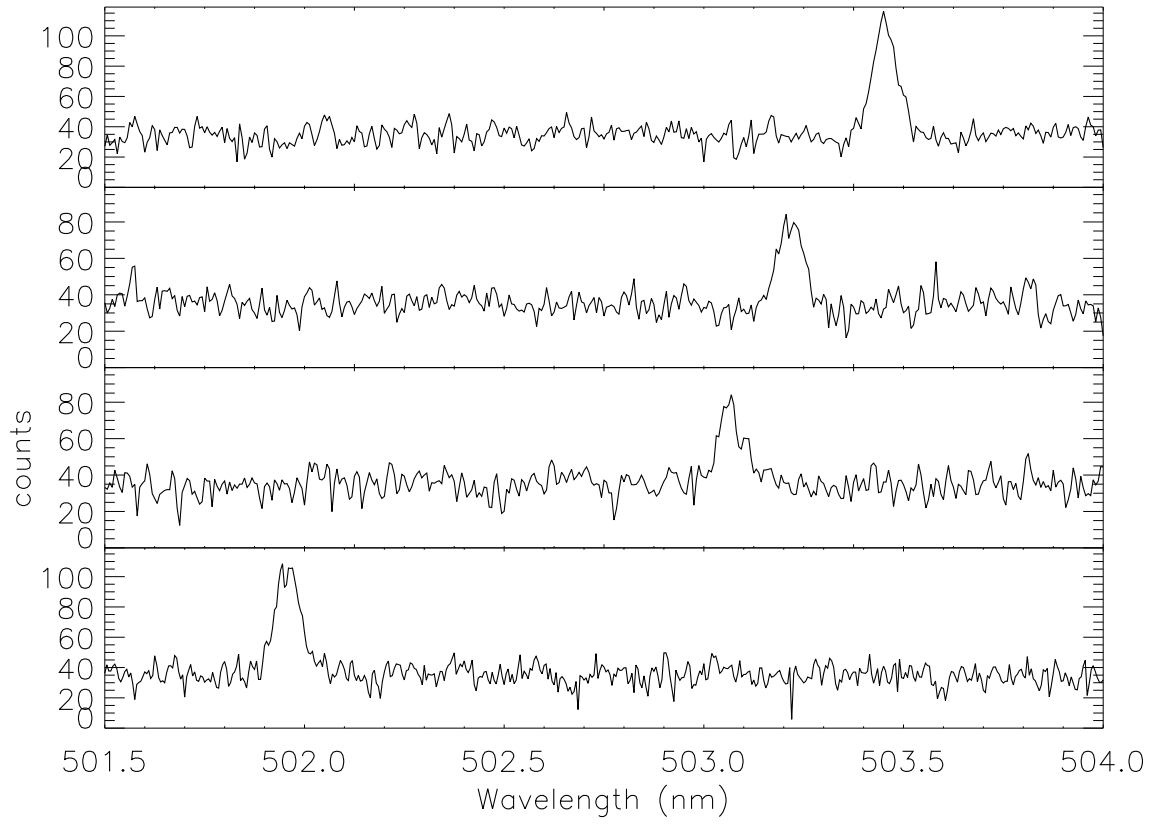


Fig. 1.— Resolved [OIII] 5007 Å emission lines of 4 spectroscopically confirmed PNs.

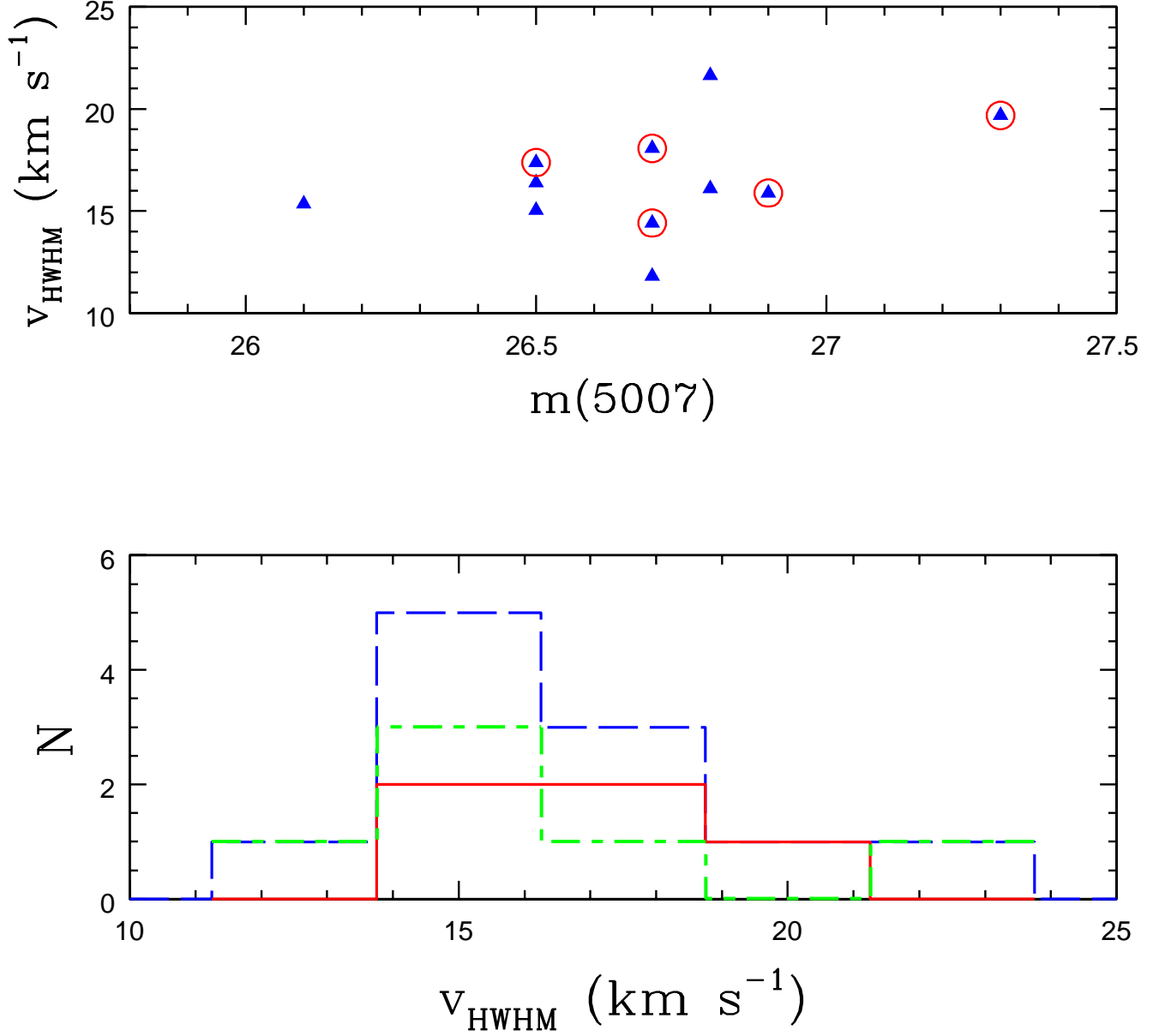


Fig. 2.— Top panel - [OIII] spectroscopic expansion velocities v_{HWHM} vs. $m(5007)$ magnitudes for the PNs from the Doherty et al. (2008) sample; the circled symbols indicate the M87 PNs. Bottom panel - histograms of v_{HWHM} measured for all PNs in the Doherty et al. (2008) sample (dashed blue lines), for the subsample bound to the M87 halo (continuous red lines), and for the PNs not bound to M87 (dash-dotted green lines). The average v_{HWHM} for the entire sample is 16.5 kms⁻¹.

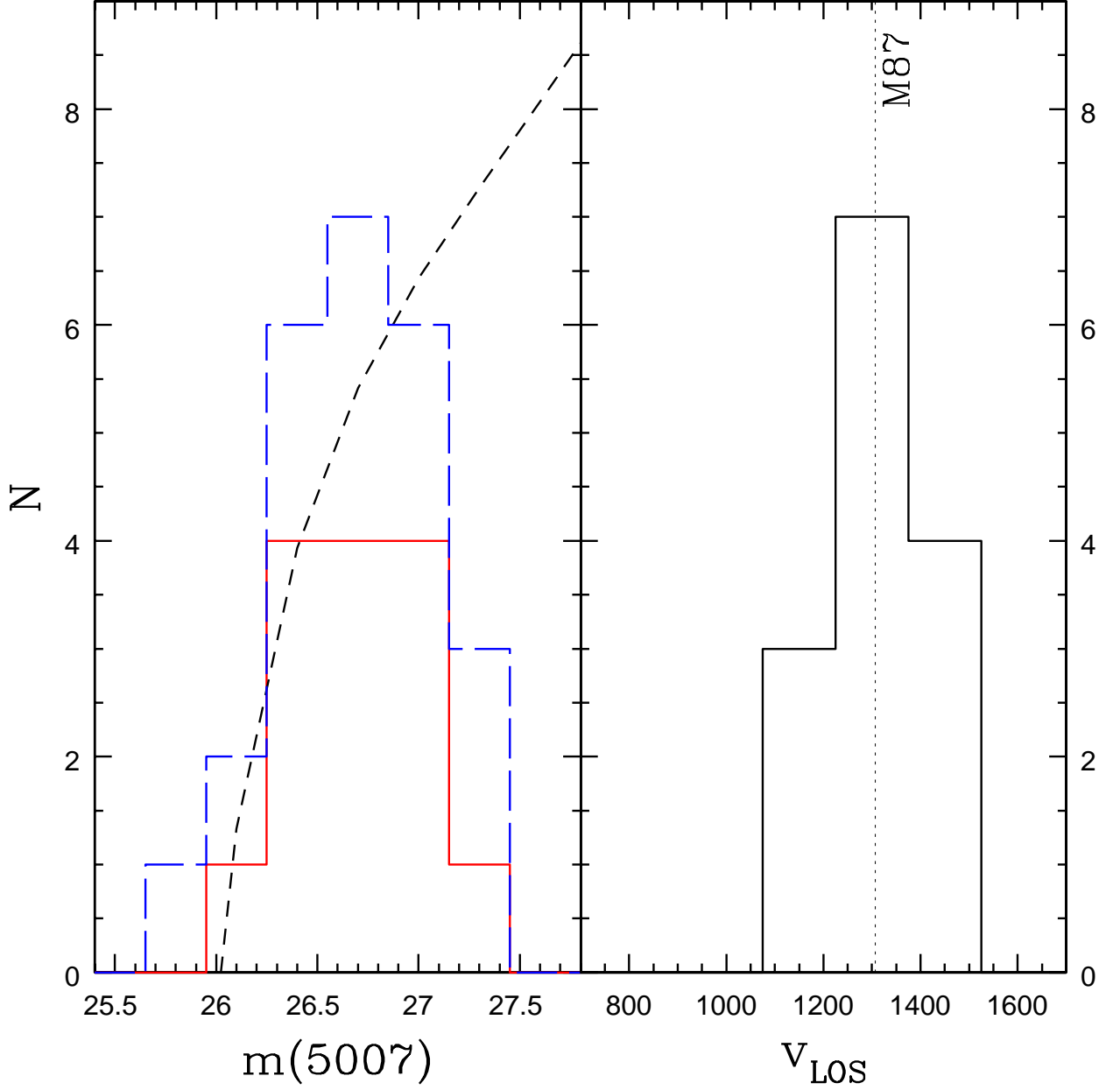


Fig. 3.— Left panel: PNLF in the surveyed fields in 0.3 mag bins. Long dashed blue line: PNLF for the entire spectroscopically confirmed sample of PNs in the Virgo cluster core at the position of the F3, F7 and F4 fields of Feldmeier et al. (2003). Red continuous line: PNLF for the PNs bound to the M87 halo. Short dashed black line: Ciardullo et al. (1989) analytical formula for the PNLF with $m^* = 26.0$. Right panel : LOS velocity distribution for the 14 PNs bound to the M87 halo. The systemic velocity of M87 is also indicated.